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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE ALTITUDE PERFORMANCE OF PENTABORANE AND A PENTABORANE - JP-4 BLEND IN AN EXPERIMENTAL 9.5-INCH-DIAMETER TUBULAR COMBUSTOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY INVESTIGATION OF THE ALTITUDE PERFORMANCE OF PENTABORANE AND A PENTABORANE - JP-4 BLEND IN AN EXPERIMENTAL 9.5-INCH-DIAMETER TUBULAR COMBUSTOR

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SUMMARY

A preliminary investigation was conducted to determine the combustion characteristics of pentaborane and a blend of 64.2 percent pentaborane and 35.8 percent JP-4, MIL-F-5624A, fuel in a turbojet combustor. The combustor tested was a current production type that was modified during the program in an endeavor to minimize oxide deposits. The combustor evolved was 4 inches shorter than the production model combustor of the same diameter. It consisted of a wire-cloth liner barrel and dome and an air-atomizing fuel nozzle. The performance of pentaborane was evaluated at four test conditions simulating flight altitudes of 40,000 and 61,000 feet at 85 and 100 percent turbojet engine speed. In addition, a test was conducted at combustor outlet temperatures higher than normally permissible in a conventional turbojet engine. The blended fuel was tested at a simulated flight altitude of 61,000 feet at 100 percent rated speed.

Oxide deposits were virtually nonexistent in the barrel and dome of the liner. The sheetmetal tailpiece of the liner collected 24 to 62 grams of deposit that, at the 100 percent rated speed conditions, appeared to have reached an equilibrium thickness. Tests of longer duration would be required to determine whether the oxide thickness at the 85 percent rated speed conditions had reached equilibrium. Combustion efficiencies ranged from 90 to 94 percent for pentaborane and were approximately 90 percent for the blend. Combustor outlet-temperature profiles had a spread of approximately 450° F at the 85 percent rated speed conditions and a spread of about 600° to 880° F at the 100 percent rated speed conditions and are considered marginal when compared with conventional practice. The combustor pressure losses were lower than those encountered in conventional turbojet combustors.

INTRODUCTION

Experimental investigations of the combustion characteristics of diborane, pentaborane, and pentaborane-hydrocarbon blends in turbojet combustors were initiated at the request of the Bureau of Aeronautics, Department of the Navy, as part of Project Zip. Tests of these fuels in 7-inch-diameter single combustors have been conducted at this laboratory (refs. 1 to 3). The preliminary results of the evaluation of diborane and pentaborane indicated it was necessary to design specific combustors for each fuel in order to reduce the tendency to deposit solid oxides on the walls of the combustor. A blend of 50 percent pentaborane in JP-4, MIL-F-5624A, fuel required further combustor modifications inasmuch as combustion stability was poor in the pentaborane combustor and deposits were excessive in the diborane combustor (ref. 3). Experimental combustors were developed that gave satisfactory performance for the three fuels at the limited test conditions and short durations investigated. Promising techniques were demonstrated for alleviating oxide deposits on turbine blades and other metal surfaces, namely, by heating or filming the surfaces with air.

The results reported herein on pentaborane and on a blend of 64.2 percent pentaborane in JP-4, MIL-F-5624A, fuel were obtained from May to September 1953 as a continuation of research reported in references 1 to 3. The research herein was conducted in a 9.5-inch-diameter single combustor, which incorporated a fuel injector and combustor liner that were evolved from a series of 30 tests using pentaborane fuel. Combustor operating conditions simulated altitudes of 40,000 to 61,000 feet, engine speeds of 85 and 100 percent rated engine speed, and a flight Mach number of 0.6. An additional test was made with pentaborane at combustor exit temperatures higher than current turbojet design practice. Data are presented on combustion efficiencies, outlet temperature profiles, pressure losses, and oxide deposits.

FUEL

Values of several of the physical properties of pentaborane and the pentaborane JP-4, MIL-F-5624A, fuel blend are as follows:

	Pentaborane[a]	64.2 Percent pentaborane[a] and 35.8 percent JP-4 by weight
Formula weight	63.17	----------
Melting point, °F	-52	----------
Boiling point, °F at 760 mm Hg	136	----------
Heat of combustion, Btu/lb	[b,c]29,127	25,310
Heat of combustion, Btu/cu ft	[d]1,170,000	[e]1,076,000
Stoichiometric fuel-air ratio	0.07635	0.0729

[a]Purity, 99 percent.
[b]Based on water in gaseous phase.
[c]Value used herein; most recent value is 29,100.
[d]Specific gravity of pentaborane taken as 0.6435 at 0° C from ref. 4.
[e]Specific gravity of blend computed for 0° C.

The melting points of the two forms of boron oxide B_2O_3 are as follows:

Crystalline, °F 842
Vitreous, °F 1070

FUEL SYSTEM AND OPERATING PROCEDURE

The fuel system is shown in figure 1 and differs in several respects from the systems of references 1 to 3. Liquid coolant was not used in the present investigation. However, methyl-cellosolve was used in most cases to buoy the fuel tank which was suspended in a chamber by a cantilever arm connected to a strain gage. The fuel tank was fitted with a siphon extending to the bottom of the cylinder and a gas inlet located at the top of the cylinder. Fuel was forced from the tank by helium pressure which was controlled by a remotely operated regulator. In several tests, the fuel tank had a single valve without a siphon. In these cases the tank was preloaded with 300 pounds per square inch of helium, inverted and suspended in air by a chain hoist. The fuel was forced from the tank by the preloaded helium. For both tank systems, the fuel flow was started and stopped by a remotely controlled, pressure operated, piston valve. The fuel flow rate was governed by a remotely operated throttle valve. When the siphonless tank was used, a nearly constant fuel flow rate was maintained by progressively opening the throttle valve as the pressure of the preloaded helium decreased. Fuel lines were purged with helium before each run and purged with helium and gasoline after the run.

Figure 2 shows details of the air-atomizing solid cone fuel injector which evolved from the development tests. Room-temperature air, from the central laboratory supply, was metered by a rotameter (fig. 1) and fed to the nozzle by ducts which surrounded a major portion of the fuel lines of the nozzle assembly and thus acted as a fuel coolant. The air flow was governed by a remotely controlled pressure operated valve and was preset prior to starting of the fuel flow. A spring loaded, variable port area valve set to open at 50 pounds per square inch was installed in the nozzle housing to prevent upstream vaporization of the fuel. The fuel and air were mixed internally and were discharged through a simple orifice. The estimated fuel pressure drop downstream of the spring load valve ranged from 3 to 8 pounds per square inch and the atomizing air pressure entering the nozzle was 4 to 15 pounds per square inch greater than the combustor pressure. The spray angle was approximately 15°.

APPARATUS

Combustor installation. - A diagram and a photograph of the combustor installation are shown in figures 3 and 4, respectively. Combustion air from the central laboratory supply was regulated by a remote control valve. The combustor inlet temperature was regulated by a heat exchanger. The exhaust products of the test chamber were discharged into an exhaust plenum where they were cooled by water sprays and discharged through an exhaust header. The header was equipped with valves to provide either atmospheric or altitude exhaust. The lowest exhaust plenum operating pressure obtainable with the altitude exhaust system was 0.45 atmosphere absolute.

Combustor. - The combustor housing was a modification of a standard tubular combustor from a J47 turbojet engine. The housing was shortened 4 inches by cutting out the expansion section and seam welding the two ends together. The combustor inlet and exit transition sections were segments of the corresponding sections of a complete engine. The downstream section was covered with a 2-inch blanket of insulation. The combustor liner developed during the course of the investigation is shown on figure 5. The central portion of the dome was fabricated of porous screen which was spot-welded to a frame which in turn was bolted to the liner. The screen was untreated, 28 by 500 mesh, stainless-steel wire cloth. A 1/6-inch annulus existed between the nozzle housing and the wire supporting framework, and an irregular shaped annulus (see fig. 5) of approximately 1/8 inch existed between the framework and the liner shell. The air flow passing through the dome was estimated to be one-tenth, or less, of the total air flow. A 14-inch length of the liner was made of 20 by 200 mesh stainless-steel wire cloth that was single sprayed, brazed, and then reduced in thickness 10 percent by calendering. These processing techniques, described in reference 5, tend to increase the tensile strength and reduce the porosity of the cloth.

After this processing, 16 secondary air holes, 3/4 by 2 inches, were cut in the downstream section of the cloth. The cloth was then spot-welded to the liner shell. A 3-inch long section of the upstream portion of the cloth was covered by a 1/32-inch-thick stainless-steel band (fig. 5), leaving an 11-inch long section of the wire cloth uncovered. A standard spark plug was used as an ignition source on runs 55 to 59. For the remaining runs, the electrodes were lengthened by 3/4 inch.

3126

Instrumentation. - Air flow was metered by an ASME orifice. The pressure upstream of the orifice, the fuel tank pressure, and the exit plenum pressure were indicated by calibrated gages. The orifice pressure differential and the total-pressure drop across the combustor P_a-P_c were indicated by water manometers. The combustor inlet and exit total pressures and the two individual total pressures at station D', shown on figure 6, were indicated by mercury manometers. The total-pressure probes in the exhaust gases were kept free of solid deposits by a continuous bleed of air through the tubes. The bleed air flow rate was sufficiently low that momentum pressure losses within the tube were considered negligible.

The fuel flow rate was recorded continuously by means of a rotating vane flowmeter (fig. 1) and a self-balancing recording potentiometer. The flowmeter measures volume flow rate and was calibrated with gasoline before each run. The weight flow rate of the test fuel was determined by the gasoline calibration and a density correction. When the siphon fitted bottle was used, the fuel weight was also recorded continuously by means of a strain gage and an oscillograph. This fuel weighing system was calibrated immediately before each run. The fuel flow rate was determined from the slope of the fuel-weight-time curve. An independent check of the flow rate was provided by weighing the fuel tank by means of a balance scale before and after each run.

Figure 6 shows the location of the thermocouples at the combustor entrance and outlet. Closed-end couples were used at the outlet stations. As shown on the figure, 15 of the couples at station D were wired individually and the remaining 20 were wired in parallel. Nine couples in parallel were located at station D' to permit a check of the average combustor-outlet temperature. Two parallel couples were used to sense the combustor-inlet-air temperature, and single thermocouples were used to sense combustor outlet-duct wall temperature at station D, orifice air temperature, and fuel temperature at the vane-type flowmeter. All couples in any parallel circuit had matched resistances to minimize measurement error. All the above temperatures were recorded at regular intervals during each test by self-balancing strip-chart potentiometers. Additional temperatures were recorded manually from the readings of indicating, self-balancing potentiometers.

3126

PROCEDURE

Test conditions. - Five test conditions were investigated as follows:

Condition	Combustor inlet total pressure, in. Hg abs	Combustor inlet temperature, °F	Air flow,[a] lb/(sec)(sq ft)	Combustor temperature rise, °F	Simulated flight condition[b]	
					Altitude, ft	Percent of rated speed
A	34	268	6.32	680	40,000	85
B	34	368	5.35	1182	44,000	100
C	15	268	2.83	680	57,000	85
D	15	368	2.38	1182	61,000	100
E	15	368	2.38	1560	------	---

[a]Air flow per unit of maximum cross-sectional area of combustor housing.

[b]Simulating a flight Mach number of 0.6 on a typical turbojet having a 5.2 compressor pressure ratio at sea-level rated speed.

Calculation. - On each run, points at time intervals of 1 minute were chosen for analysis.

Combustion efficiencies were computed from the following approximate relation:

$$\eta_b = \frac{\text{Equivalence ratio theoretically required for measured temperature rise}}{\text{Actual equivalence ratio}}$$

The theoretically required equivalence ratios for a measured temperature rise using pentaborane fuel were determined from the data of reference 6. For the pentaborane - JP-4 blend, the theoretically required equivalence ratios were determined from unpublished results by the method and assumption described in reference 7.

The average combustor outlet temperature was computed as an arithmetic mean of the 35 outlet thermocouple indications. This was achieved by assuming that each of the 20 thermocouples in parallel sensed a temperature equal to the temperature recorded for the parallel circuit. No correction was made for radiation or velocity effect on the thermocouples.

The rotating-vane method appeared to be more accurate than the strain-gage method of determining fuel flow rate and therefore was used in the reported data.

The total-pressure loss through the combustor was computed as the dimensionless ratio of the measured total-pressure drop $P_a - P_c$ to the calculated reference dynamic pressure q_r. The value of q_r was computed from the combustor inlet density, the air flow rate, and the maximum cross-sectional area of the combustor housing, 0.48 square foot.

3126 Accuracy. - The accuracy of the combustion efficiency data was affected primarily by the exhaust products, temperature measurements, and the fuel rate measurements.

Radiation and thermocouple conduction corrections for temperatures indicated by the combustor outlet thermocouples were not made. For the tests reported herein the walls of the exhaust duct heated up slowly throughout each run. Outlet temperature readings likewise increased, particularly in the high outlet temperature runs, and, consequently, higher combustion efficiencies were indicated as the run progressed. The effect of increasing combustion efficiency with increasing outlet duct wall temperature is illustrated on figure 7.

For each run, the net fuel weight obtained on the balance scale was compared to the fuel weight determined by integration of the area under the flow rate-time curve obtained with the flowmeter. With exception of run 60, where fuel-flow rate data are questionable, the agreement between the balance and flowmeter methods of determining the weight fuel consumption was 2.5 percent. On run 60, condition C, the flow rate as measured by the flowmeter was increased by the ratio of the net balance weight to the integrated fuel weight. This action was considered justifiable, since the flow rates for this run were near the low limit range of the flowmeter.

DESIGN CONCEPTS

The development work on the 7-inch-diameter combustor and fuel injection system for pentaborane and the 50-percent pentaborane - JP-4 blend (refs. 2 and 3) gave the following indications:

1. Recirculation and turbulence of the combustion air upstream and for several inches downstream of the fuel injector should be minimized.

2. The jet of liquid fuel should not impinge on the walls of the combustor.

3. The spark ignition electrodes should not be placed near the fuel injection zone since the electrodes introduce surfaces where the deposits could form and thereafter bridge to the injection nozzle.

The simple orifice-type nozzle and combustor liner used in references 2 and 3 had several serious drawbacks. The pencil-like stream of fuel issuing from the nozzle tended to pierce the secondary air stream to produce local hot spots in the combustion products. This excessive fuel-jet penetration would tend to limit the maximum injection pressure and thereby seriously limit the useful flow rate range of the nozzle. The pentaborane combustor permitted approximately 25 percent of the air to enter the dome, thereby reducing the amount of secondary air. This effect further complicated the attainment of a better combustor outlet temperature profile.

For the present 9.5-inch-diameter combustor program, it appeared necessary to sidestep the shortcomings of the previously developed 7-inch- 3126
diameter combustors and fuel nozzles. The ratio of air entering the dome to the total available air was reduced to a value of approximately 10 percent. Cone-type sprays were used. Furthermore, methods of air filming the combustor liner wall were attempted in an endeavor to further eliminate oxide deposits. Except as noted, pentaborane was used for all tests.

The first combustor system tested used a 30°, hollow cone spray nozzle, and a modified liner (fig. 8) having many small slots along the liner that tended to introduce air parallel to the liner wall. Deposits obtained during a run with this configuration are shown in figures 9(a) and (b). Deposit buildup can be observed in the region where the fuel spray may have impinged on the liner walls. Also, the small air slots did not adequately prevent oxide deposition.

Experiments conducted with a series of wire-cloth liners similar to the liner of figure 5 showed that if the fuel spray could be prevented from impinging on the cloth, oxide deposits could be eliminated. Wire cloths of three different porosities were tested. Porosity characteristics of the cloths are shown on figure 10. Cloth A was sufficiently porous to eliminate oxide buildup completely; however, with so much of the air entering through the porous cloth, there was insufficient air entering in the secondary air jets to penetrate adequately into the hot gases and produce a uniform outlet temperature profile. Cloth B was of too low a porosity to air-film the surface adequately, and oxide deposits occurred. Cloth C appeared to be a good compromise and was used for the tests reported herein. It was of less porosity than cloth A and did not permit the oxides to block the passageways between the wires, although a fine oxide coating would occasionally form on the outer surfaces of the wires.

During the course of the development work, the barrel of the liner was shortened 4 inches for the following reasons:

1. A greater percentage of the liner surface would be wire-cloth covered without depleting the quantity of air entering in the secondary air jets.

2. It would be expected that pentaborane would require a smaller combustion volume than gasoline or JP fuels, hence, a saving in engine length and weight could be achieved.

A variety of hollow-cone fuel nozzles were investigated. All the tests resulted in excessive deposits in the region of the liner where the spray impinged. A solid-cone nozzle with a narrow angle spray appeared to be of some promise; however, the flow-rate range of this particular nozzle was relatively small. Finally, the spray characteristics of a variety of air-atomizing nozzles were studied because the spray characteristics are less dependent on fuel flow rate. The nozzle shown on figure 2 was selected because it produced a fine spray at relatively low pressures and flow rates of the air used in it.

RESULTS AND DISCUSSION

The results of the tests obtained in the developed combustor are presented in chronological order in table I. Complete data for run 63, the highest combustor-outlet temperature condition, are not presented. The run was included, however, since the oxide deposition characteristics at these elevated temperatures are of interest. Some of the significant results of the pentaborane tests and the pentaborane - JP-4 fuel blend test are discussed in the following paragraphs.

Pentaborane Results

Eight tests, or runs, with pentaborane were attempted and of these, three runs were unsuccessful. On one run in which the inverted fuel bottle was used, caked material drained from the tank and clogged a fuel screen near the tank. The material appeared to be a solid decomposition product of the pentaborane. On another run, the fuel ignited after a combustible mixture collected in the exit plenum, resulting in a ruptured blow-out disk. In the third run, run 57, malfunctioning of the fuel nozzle occurred as discussed in detail in a following section of the report. The remaining five runs, 55, 56, 60, 61, and 63, are discussed in this section.

<u>Oxide deposition</u>. - Deposits on the combustor liner and outlet transition section for test conditions A through E are shown on figures 11 through 15, respectively. Figure 12(c) shows the fuel-injection nozzle and spark plug after a run. Nozzles and spark plugs for the other runs were of comparable cleanliness. On all these tests, the wire-cloth portion of the liner barrel had 3 grams, or less, of deposits (table I). The portion of the liner upstream of the cloth contained less than 3 grams of deposits. All the deposits upstream of the wire cloth barrel were a white dust-like material presumed to be

pure boron oxide. The deposits on the tailpiece (the sheetmetal liner surface downstream of the wire-cloth barrel) ranged from 24 to 62 grams and were greatest at the highest temperature encountered, condition E. The physical characteristics of these deposits were related to the combustor outlet temperature. At the lower combustor outlet temperature conditions, A and C, the deposits resembled those on the wire-cloth barrel and dome, but were somewhat more granular and cohesive (figs. 11(a) and 13(a)). At the higher temperature conditions, B, D, and E, the deposits consisted of wave-like formations of brittle glass (figs. 12(a), 14(a), and 15(a)). Also, these deposits were thickest near the bottom surfaces of the tailpiece, indicating that the liquid oxides flowed downward as well as axially along the tailpiece. Presumably, deposits that formed during the high-temperature tests had reached an equilibrium film thickness. Tests of a longer duration would be required to determine whether the granular deposits formed during the low temperature tests had likewise reached an equilibrium thickness. 3126

Deposits on the transition section (parts (b) of figs. 11 through 15) resembled the deposits on the tailpiece. As shown on the figures, these deposits were thickest at the line of engagement between the transition section and the tailpiece which protruded approximately 1/2 inch into the transition section. Although the quantity of fuel used per test was greater for the runs reported herein than for the pentaborane runs of reference 2, the weights of deposits in the present combustor liner were considerably less than those for the referenced liner.

Pressure losses. - The combustor total-pressure losses are listed on table I for conditions A, C, and D. The tip of the downstream pressure probe melted off during the early portion of the test at the other two conditions. Based on the available data, the pressure losses remained constant throughout the course of each test and were from 11 to 13 times the combustor reference dynamic head. These losses are equal to or smaller than losses for conventional combustors and illustrate that air filming of the porous cloth requires only moderate pressure losses across the cloth.

Temperature profiles. - Outlet-temperature profiles for test conditions A, B, and D, runs 56, 55, and 61, respectively, are shown on figures 16(a), (b), and (c) for data points near the beginning and end of each run. The data serve to illustrate that the temperature profile pattern remained relatively constant throughout a run.

As would be expected, temperatures were highest near the center of the duct. The spread between the maximum and minimum temperatures was approximately 450° F at test condition A. At condition D (1550° F outlet temperature and 1/2 atmosphere combustor pressure) the spread was about 600° F as compared with a spread of approximately 880° F at condition B (1550° F outlet temperature and 1 atmosphere combustor pressure).

A temperature spread of 400° to 500° F is considered desirable for conventional practice; therefore, the temperature spread at conditions B and D may be considered marginal.

The outlet-temperature profiles for test condition C (run 60) are shown on figure 17 for three different ratios of atomizing-air flow rate to pentaborane flow rate W_a/W_f. A decrease in this ratio from 0.68 to 0.19 improved the profile by reducing the temperature spread from 556° to 310° F. Bench tests using water in place of fuel indicated that the nozzle spray angle was the widest at the lowest flow ratio tested in the combustor. Since the ratio of atomizing air to fuel flow was not varied at conditions A, B, and D, it can only be surmized that the temperature profiles could be improved by variations in atomizing-air flow.

In summary, the combustor-outlet-temperature spreads described in the preceding paragraph ranged from 10 to 40 percent lower than the spreads for comparable test conditions reported in reference 2 for pentaborane except for condition D. Furthermore, the outlet profiles presented herein were obtained at combustor pressure-loss values lower than those of the referenced data.

Combustion efficiency. - Since combustion efficiency at the 1550° F combustor outlet temperature increased with increasing wall temperature (fig. 7), the efficiency values used for discussion purposes were selected from data points near the termination of each test. At the higher outlet temperatures, conditions B and D, the combustion efficiency was 90 to 93 percent (table I). An efficiency of 94 percent was obtained at condition A.

The combustion efficiency at condition C, the test in which the atomizing-air flow was varied, ranged from 83 to 92 percent. The effect of atomizing-air flow on combustion efficiency is obscured by the relative inaccuracy of the fuel flow rates for run 60.

Combustor efficiency values previously reported in reference 2 for pentaborane in a 7-inch-diameter combustor were as follows: 94 at condition A, 95 to 102 at condition B, 92 at condition C, and 86 at condition D. In an over-all comparison, the combustion efficiencies reported herein are about the same as those reported in reference 2.

Ignition characteristics. - During this series of tests, ignition of the fuel usually was not achieved at the standard operating conditions. When ignition did not occur within 3 seconds after the fuel throttle valve was opened, the air flow rate was decreased and the fuel rate increased until ignition occurred. Then the flow rates were adjusted to the prescribed test condition. It was during a start of this type, run 59, that the explosion occurred in the exit plenum. By increasing the spark electrodes 3/4 inch, ignition was more easily attained but usually required adjustment of the air and fuel throttle settings. The aforementioned ignition difficulties are attributed to the lack of large-scale swirl eddies in the combustion zone, a desirable characteristic from the standpoint of deposits. In preference to the use of still longer electrodes, which might incur oxide deposits, a retractable type spark plug (ref. 8) appears desirable.

Pentaborane - JP-4 Blend Results

3126

The results of the single test with a blend of 64.2 percent pentaborane and 35.8 percent JP-4 at test condition D are given in table I. The combustion efficiency was 89 percent or 4 percent lower than recorded for pentaborane at the same test condition. Photographs of the oxide deposits on the liner and transition piece are shown on figure 18. The apparent physical characteristics of the deposits, as well as the quantity of deposits, were similar to those obtained with pentaborane fuel at the same test condition; however, the blend furnished the only case of spalling oxides (fig. 18(b)) observed during the tests reported herein. The combustor pressure losses with the blend fuel were equal to those for pentaborane as would be expected. Near the termination of the two respective tests, the spread between maximum and minimum outlet temperatures was 657° F for the blend (fig. 19) as compared with 562° F for pentaborane. The blend ignited with only slightly greater difficulty than was encountered with pentaborane.

Reliability of Apparatus

The combustor-outlet-temperature profiles and spread of the outlet temperatures previously discussed for runs 55, 56, 61, 62, and 63 remained nearly constant during each run, nor were deposits observed within the fuel nozzle orifices. Unfortunately, a similar statement cannot be made for run 57, which was conducted at test condition C with pentaborane. Upon inspection after the run, deposits were observed adhering to the inner surfaces of the fuel nozzle tip (fig. 20). Deposits on the dome and tailpiece were considerably heavier than obtained during run 60 at the same test condition (table I). Figure 20(b), a photograph of the deposits in the transition section, shows both glass and granular deposits where the tailpiece engages the transition section. Also several thermocouple rakes contain thicker deposits than observed on previous runs.

The irregularity in physical character and thickness of the deposits would indicate that a relatively poor temperature profile existed during this run. This observation is substantiated by the outlet temperature profile data of figure 21. The temperature spread 2 minutes after ignition

was 680° F as compared with a spread of 556° F for run 60, test condition C, in which the ratio of atomizing-air to fuel flow rate was least favorable for uniform profile. As run 57 progressed, the profile spread continued to increase. The relatively poor temperature profile and related nonuniformity of deposit buildup in the transition section are attributed to the fouled fuel nozzle. The fouling may have occurred during the several attempts made to ignite the pentaborane. Prior to successful ignition, the throttle valve had been opened and closed
3126 several times and the combustor air flow decreased to very low values.

This run is of interest because it indicates a potential problem involved in the use of pentaborane. The fouled fuel nozzle and its attendent deterioration of combustor performance could be remedied by taking steps to prevent oxidation of fuel in the nozzle such as a better location of the igniton source for more positive starts (see previous discussion on ignition characteristics) and a purge of fuel lines immediately after the fuel flow is stopped. In any event, to ensure reliable operation, attention must be focussed upon the design and operation of the fuel nozzle.

SUMMARY OF RESULTS

The results obtained in this investigation of pentaborane at four test conditions simulating flight altitudes of 40,000 and 61,000 feet at 85 and 100 percent turbojet engine speed, and for a fuel consisting of 64.2 percent pentaborane in JP-4 fuel at 61,000 feet at 100 percent engine speed are as follows:

1. An experimental combustor 4 inches shorter than a conventional turbojet combustor, fabricated by using porous wire cloth in the dome and barrel of the liner and using an air-atomizing fuel nozzle, indicated promising combustor performance.

2. Deposits on the barrel and dome of the liner were negligible for test durations as long as 20 minutes.

3. Smooth and stable combustion was obtained with either pentaborane or the pentaborane - JP-4 fuel blend in the same combustor. Combustion efficiencies ranged from 90 to 94 percent for pentaborane except during one run when the fuel nozzle atomizing-air flow was increased beyond its proper value, which adversely affected performance. The combustion efficiency of the blend, which was tested at a single operating condition, was approximately 90 percent.

4. Combustor-outlet-temperature profiles had a spread of approximately 450° F at the 85-percent rated engine speed conditions and a

spread of about 600° to 880° F at the 100-percent rated speed conditions, and are considered marginal when compared with conventional practice. The combustor pressure losses were lower than encountered in conventional turbojet combustors.

5. The use of pentaborane as a fuel introduces a potential problem in the fouling of the fuel nozzle because of the tendency of the pentaborane to oxidize and form solid deposits in the fuel nozzle when the fuel flow is stopped, such as in a series of successive engine starts. 3126

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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3126

TABLE I. - OPERATING CONDITIONS AND RESULTS

Run	Test condition	Time from ignition to fuel off, minutes	Time data recorded, minutes	Combustor inlet temperature, T_B, °F	Combustor inlet total pressure, P_A, in. Hg abs	Air flow, lb/(sec)(sq ft)	Fuel flow, lb/sec	Equivalence ratio	Ratio by weight of atomizing air flow to fuel flow	Combustion efficiency, percent	Combustor velocity, ft/sec	Average combustor outlet temperature, T_D, °F	Maximum individual outlet temperature, °F	Minimum individual outlet temperature, °F	Wall temperature at station D, °F	Pressure losses across combustor, $\frac{P_A-P_C}{q_r}$	Deposit on wire cloth, grams[a]	Deposit in dome, grams[b]	Deposit in tailpieces, grams[c]	Nozzle deposit (outside)
Pentaborane																				
55	B	4.4	0	360	31.1	5.31	-------	------	----	----	106	----	----	----	----	9.53	2	2	32	0
			1.0	357	32.1	5.27	0.0331	0.1707	0.13	88.5	101	1557	1900	1038	822	----				
			1.9	353	32.1	5.30	.0329	.1687	.13	88.4	101	1544	1910	1032	1025	----				
			2.9	353	32.2	5.38	.0329	.1682	.13	90.8	103	1552	1920	1032	1128	----				
			3.9	354	32.2	5.39	.0328	.1652	.13	91.5	103	1557	1905	1016	1145	----				
56	A	9.4	0	272	31.7	6.28	-------	------	----	----	109	----	----	----	----	9.4	2	2	29	0
			2.0	260	31.9	6.51	0.0192	0.0798	0.22	94.8	112	900	1179	723	495	11.5				
			4.0	273	32.8	6.39	.0207	.0881	.21	93.1	108	985	1269	765	560	12.0				
			6.0	273	32.9	6.35	.0205	.0876	.21	94.3	107	974	1262	795	642	12.0				
			8.0	271	32.9	6.37	.0208	.0886	.21	93.5	107	975	1270	818	707	12.0				
57	C	21.4	0	266	14.3	2.83	-------	------	----	----	109	----	----	----	----	9.7	3	6	67	2
			2.0	267	14.7	2.82	0.00910	0.0872	0.48	87.2	106	918	1289	609	----	11.8				
			5.0	269	14.7	2.80	.00908	.0881	.48	88.3	105	927	1351	615	----	11.8				
			8.0	268	14.8	2.81	.00885	.0866	.49	87.7	104	925	1380	610	----	11.8				
			11.0	266	14.9	2.88	.00835	.0787	.52	86.8	106	917	1391	621	----	11.7				
			14.1	268	14.8	2.81	.00901	.0863	.48	91.5	106	938	1458	624	----	11.6				
			17.0	271	14.8	2.82	.00895	.0861	.51	97.6	105	983	1550	648	----	11.6				
			20.0	268	14.9	2.82	.00880	.0847	.52	98.0	104	975	1540	646	----	11.9				
58	C	← Fuel filter plugged with decomposed pentaborane →																		
59	C	← Hard start →																		
60	C	13.3	0	273	14.2	2.79	-------	------	----	----	108	----	----	----	----	10.2	2	1	24	0
			1.0	269	14.7	2.83	0.00985	0.0945	0.85	85.7	106	955	1240	726	398	12.0				
			4.0	271	14.7	2.82	.0102	.0980	.88	87.3	108	994	1304	748	530	11.9				
			7.0	279	14.7	2.79	.0100	.0975	.31	89.2	106	1008	1265	830	600	12.2				
			10.0	279	14.3	2.78	.00982	.0961	.19	92.0	108	1017	1204	894	680	12.2				
			13.0	276	14.4	2.78	.0100	.0976	.34	83.0	107	980	1191	765	695	12.1				
61	D	12.6	0	378	13.6	2.29	-------	------	----	----	107	----	----	----	----	9.7	3	2	39	0
			2.0	376	14.1	2.28	0.0142	0.1695	0.27	88.0	102	1825	1855	1249	876	12.9				
			5.0	374	14.1	2.29	.0142	.1878	.28	87.0	102	1534	1869	1325	1068	12.6				
			8.0	371	14.5	2.31	.0137	.1618	.29	89.3	100	1821	1866	1330	1148	12.4				
			11.0	368	14.5	2.32	.0137	.1603	.50	93.3	100	1555	1908	1346	1218	12.4				
64.2 Percent pentaborane and 35.8 percent JP-4, MIL-F-5624A fuel by weight																				
62	D	8.1	0	360	14.1	2.39	-------	------	----	----	105	----	----	----	----	9.7	2	2	29	0
			1.0	366	14.7	2.36	0.0171	0.2063	0.30	82.5	100	1500	1885	1210	742	12.9				
			3.0	370	14.6	2.35	.0161	.1970	.22	86.9	100	1514	1871	1220	1070	12.6				
			5.2	372	14.6	2.32	.0161	.1970	.35	88.6	100	1534	1890	1240	1180	12.4				
			7.2	373	14.6	2.32	.0164	.2020	.32	89.2	100	1570	1934	1277	1255	12.4				
Pentaborane																				
63	E	6.4	0	368	14.2	2.38	-------	------	----	----	104	----	----	----	----	----	2	2	62	1
			8.0	380	15.0	2.32	-------	------	----	----	98	>1925	>2400	1580	1578	----				

[a]Wire-cloth barrel of liner.

[b]Portion of liner upstream of barrel.

[c]Sheetmetal portion of liner downstream of barrel.

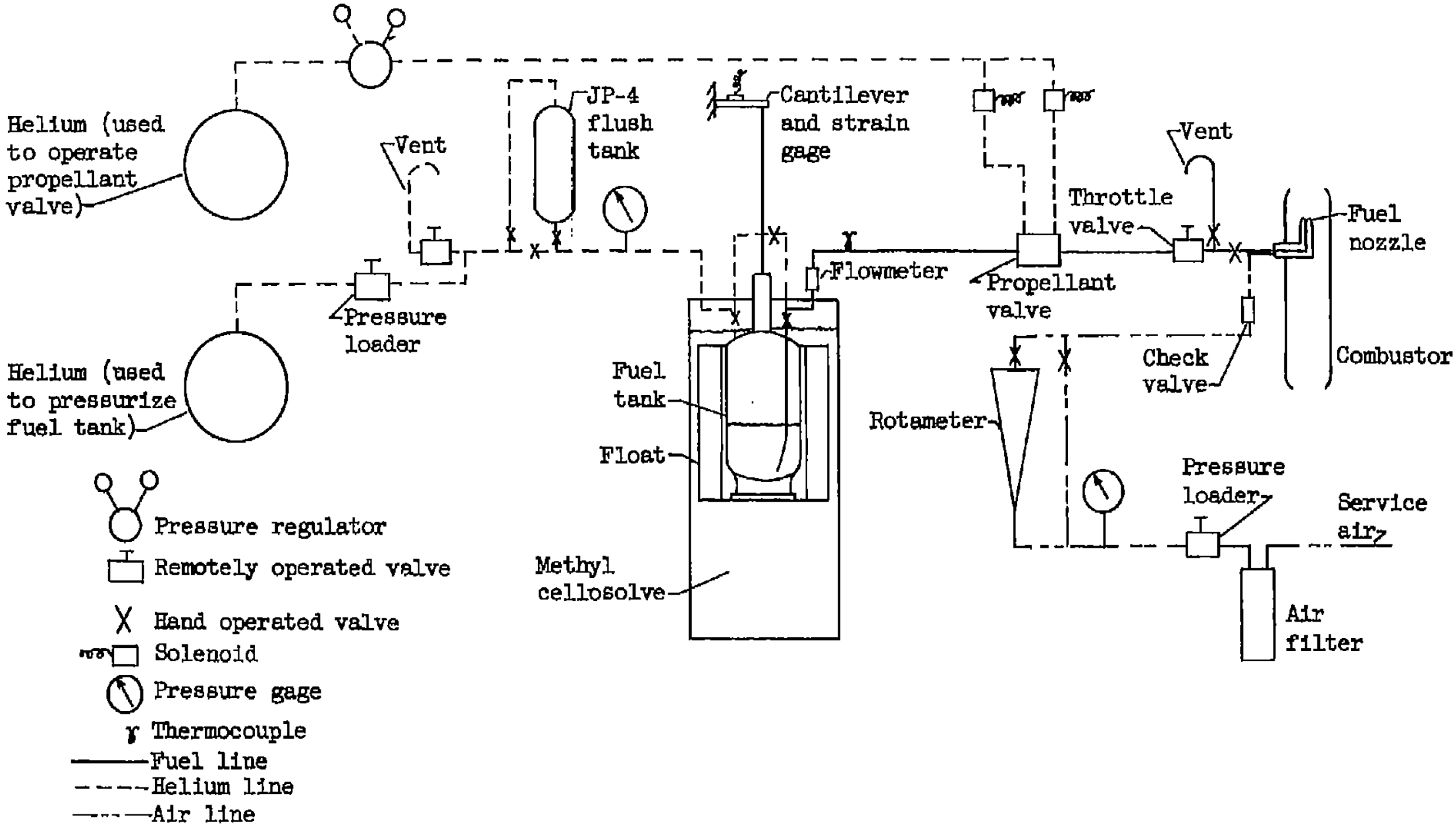


Figure 1. - Fuel system.

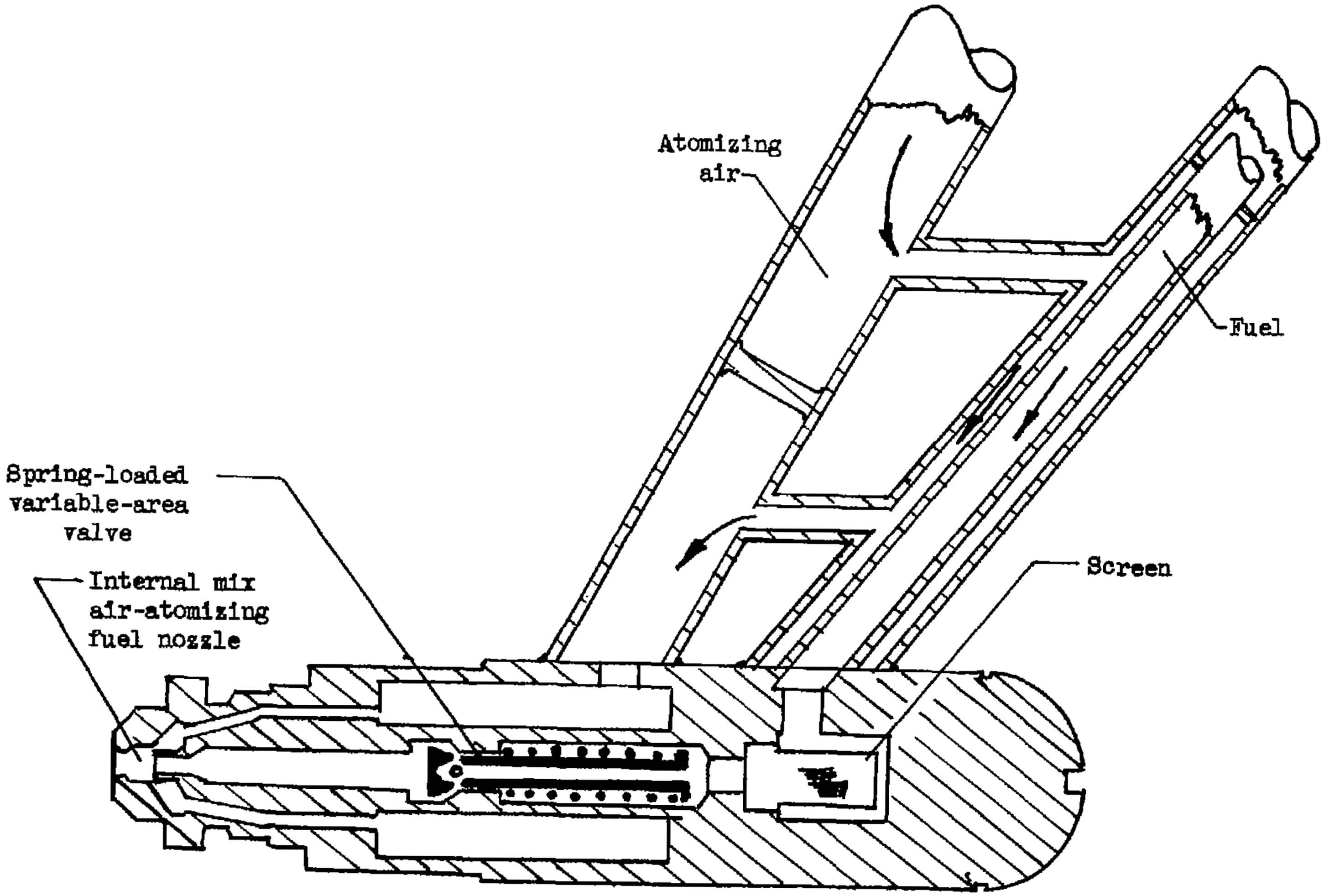


Figure 2. - Fuel-injection nozzle.

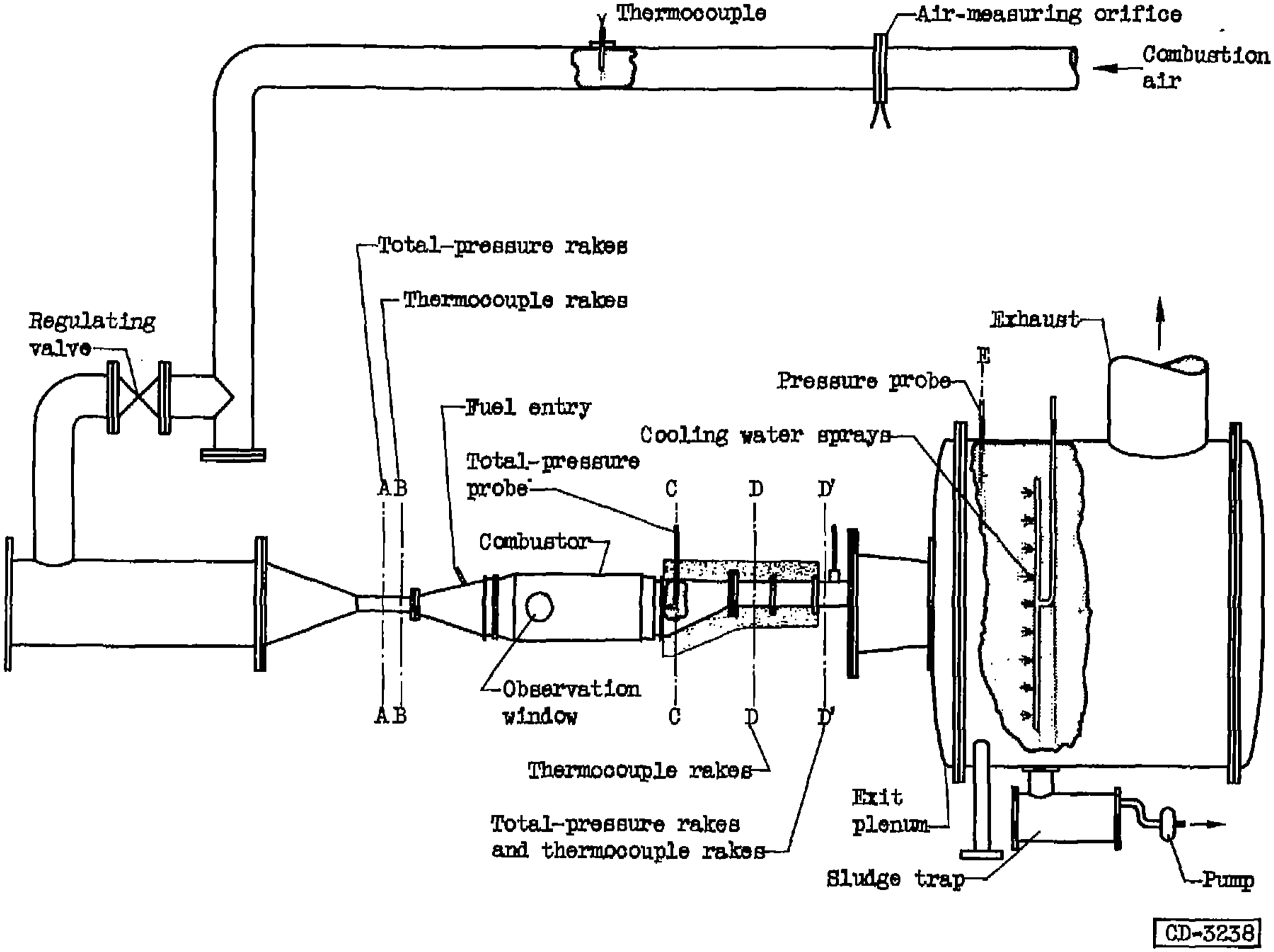


Figure 3. - 9.5-Inch diameter combustor installation.

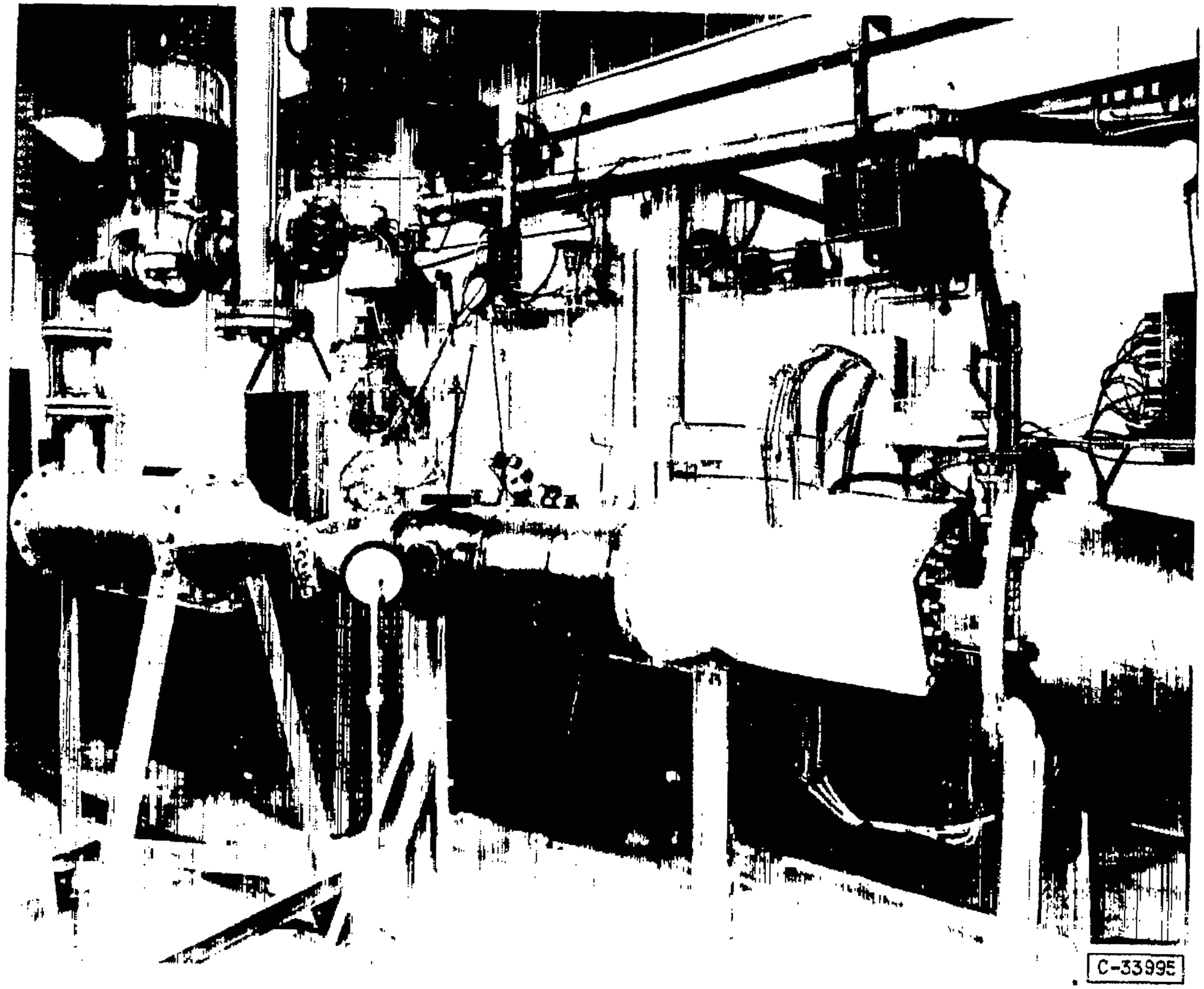


Figure 4. - Combustor installation.

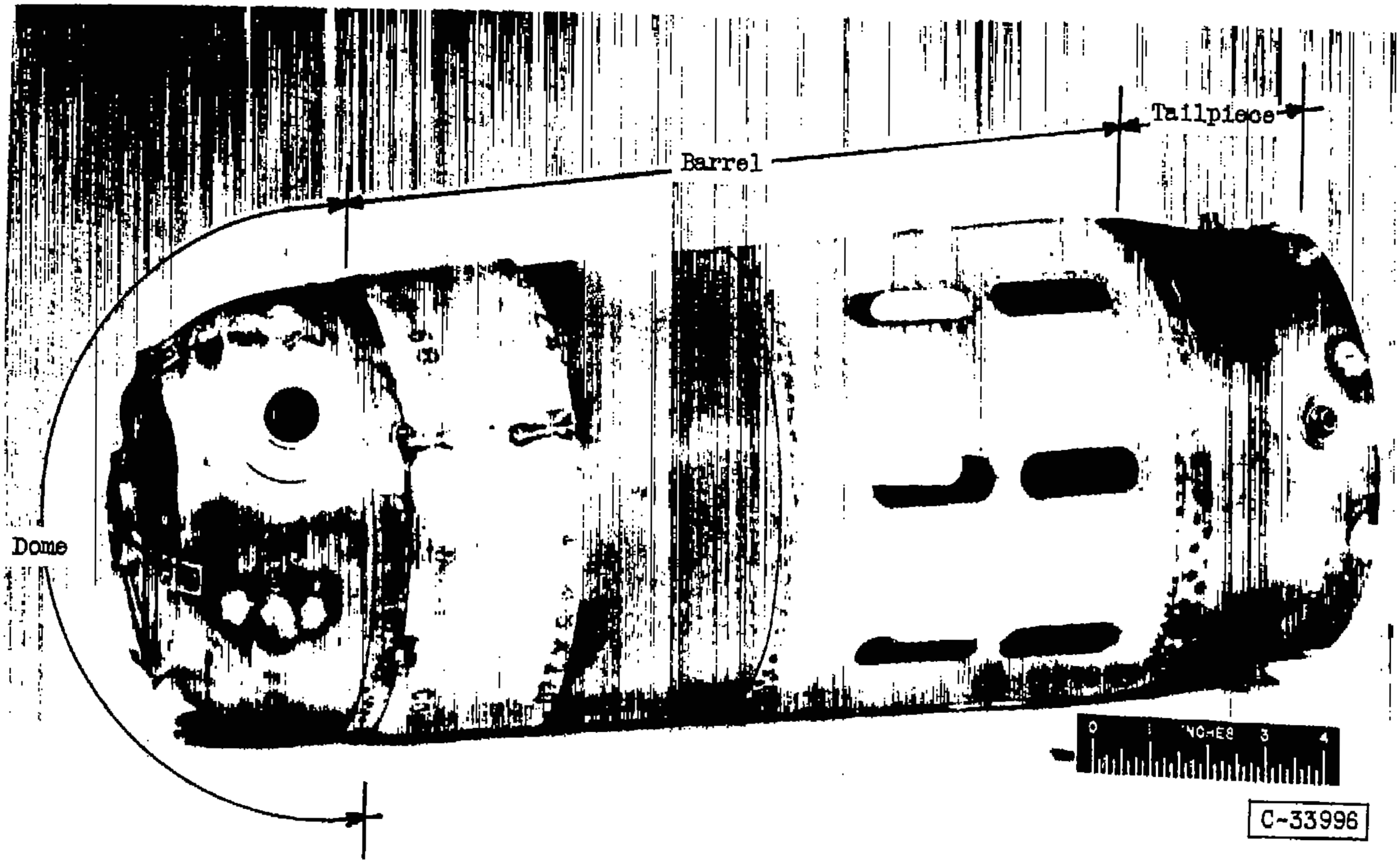
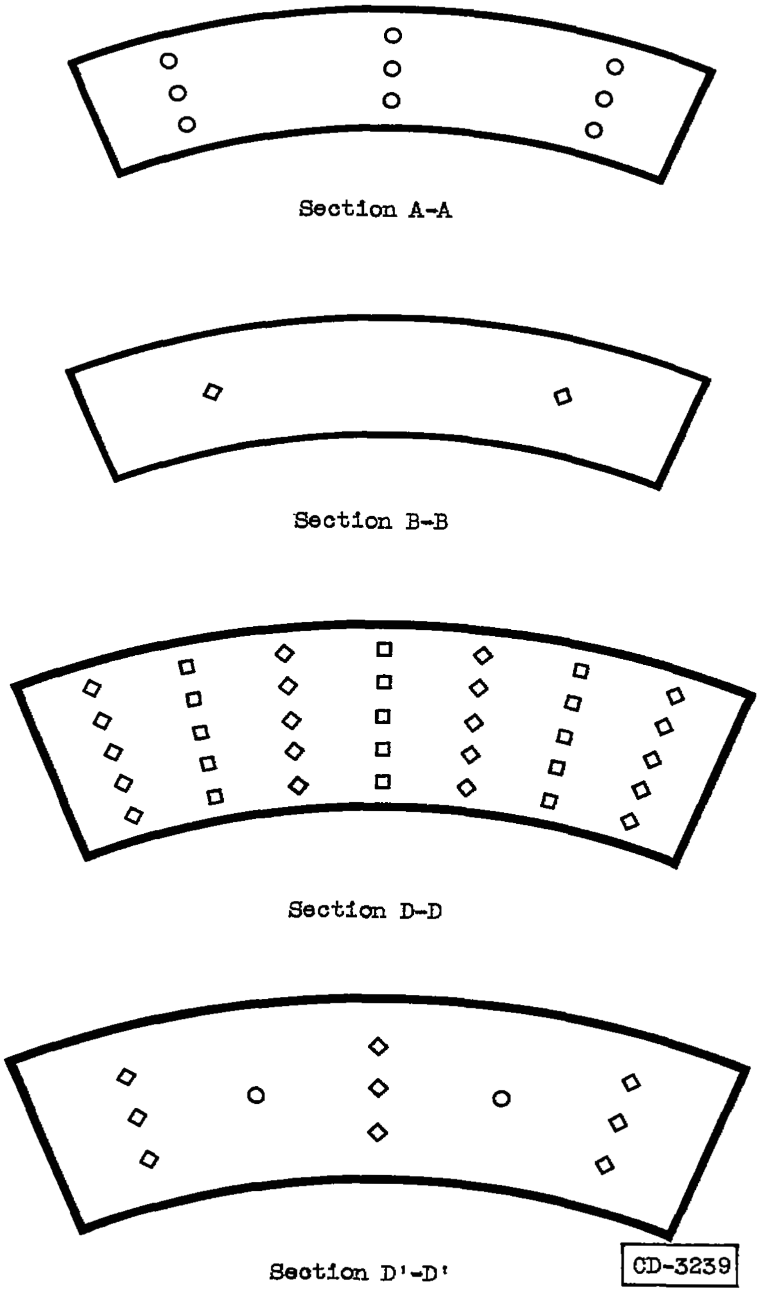


Figure 5. - Combustor liner.

3126



○ Total-pressure tubes
□ Thermocouples (wired individually)
◇ Thermocouples (wired in parallel)

Figure 6. - Instrumentation sections.

3120

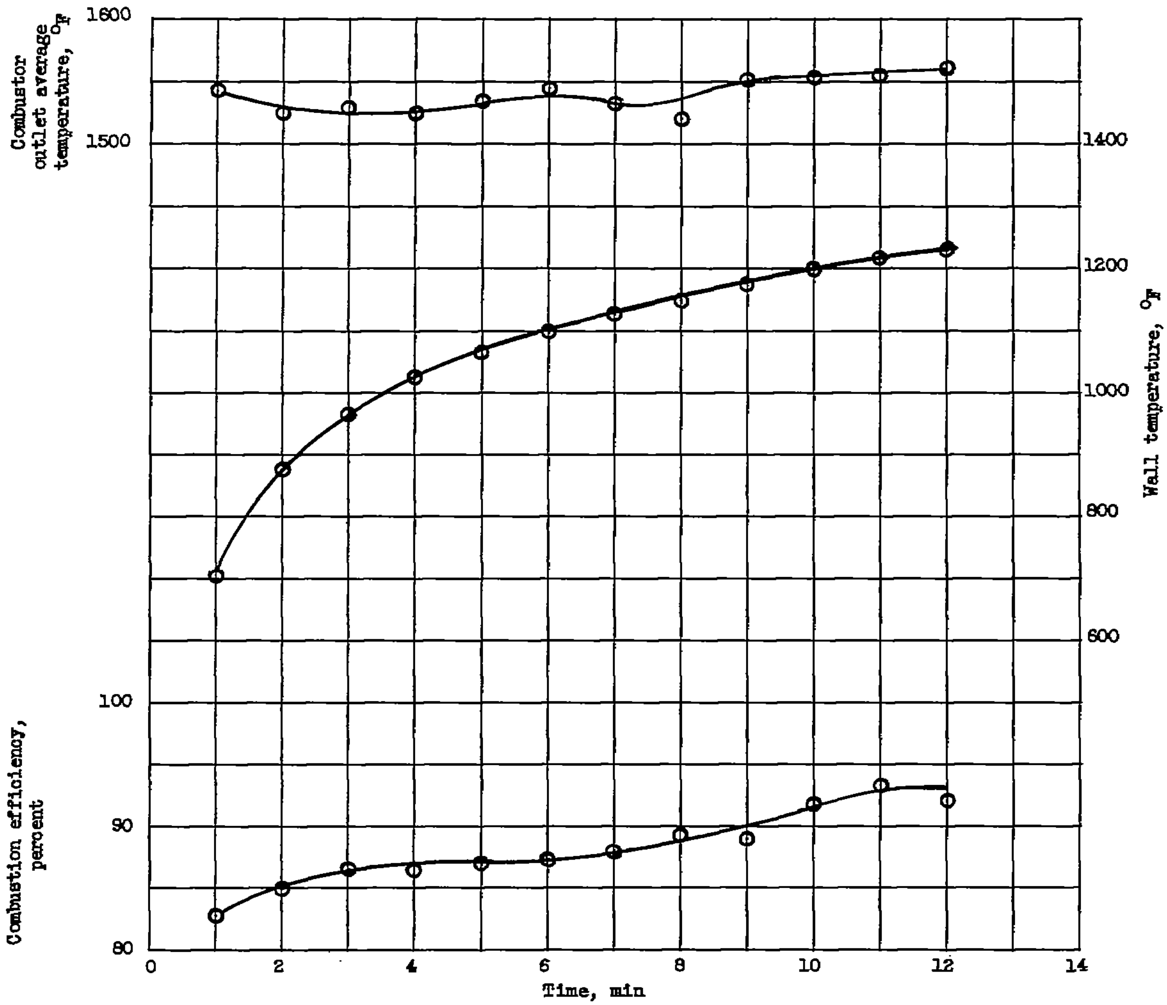
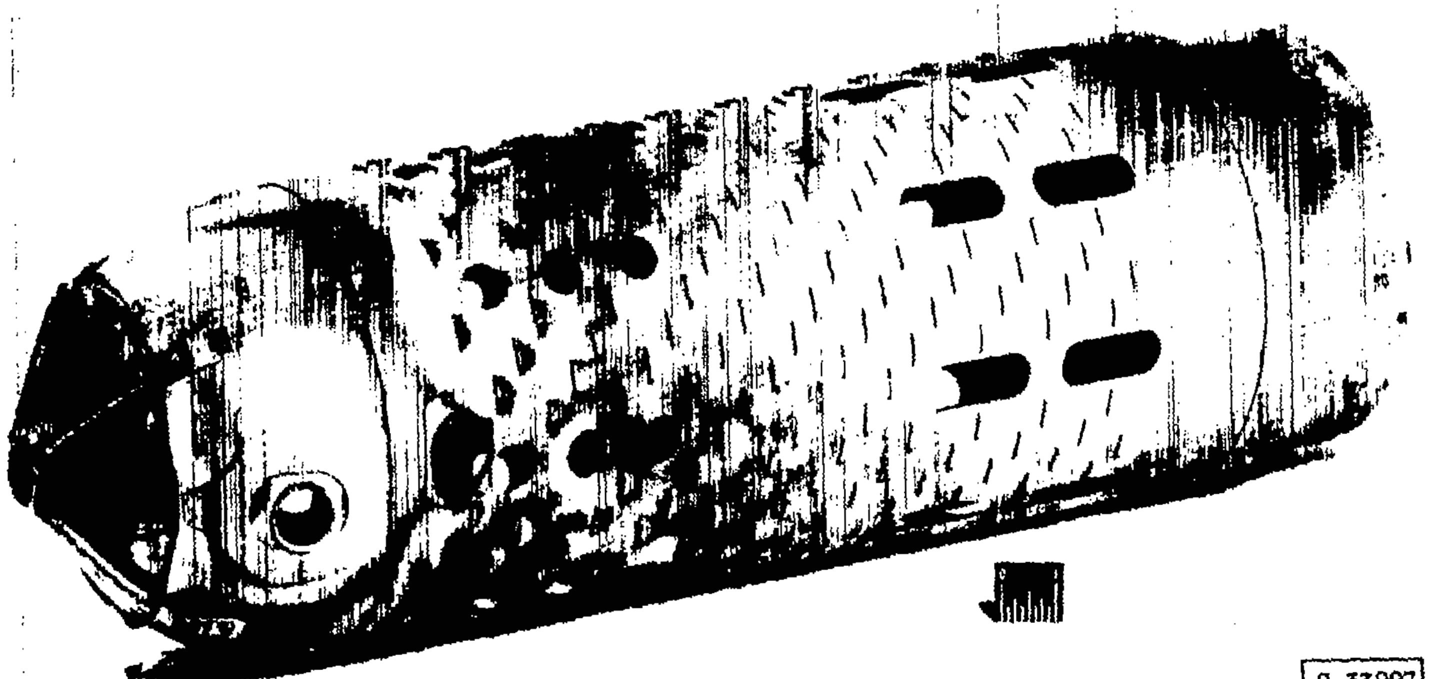
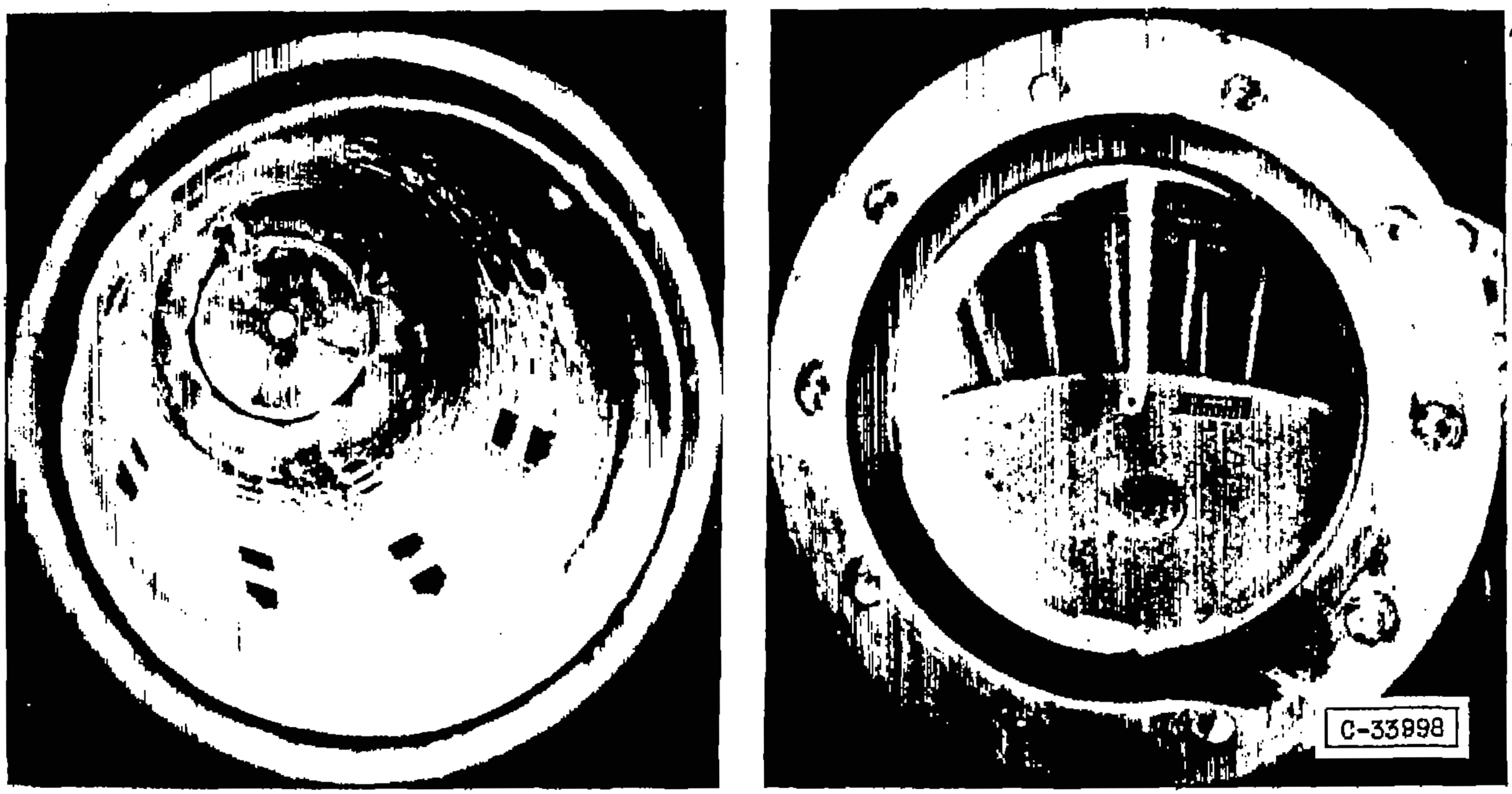


Figure 7. - Effect of thermocouple radiation losses on computed combustion-efficiency values. Data obtained from run 61 for combustion of pentaborane at test condition D.



C-33997

Figure 8. - Combustor liner used in run 34.



(a) Combustor.

(b) Transition section.

Figure 9. - Deposits obtained during run 34 from combustion of pentaborane. Test duration, 6.0 minutes at condition C.

3126

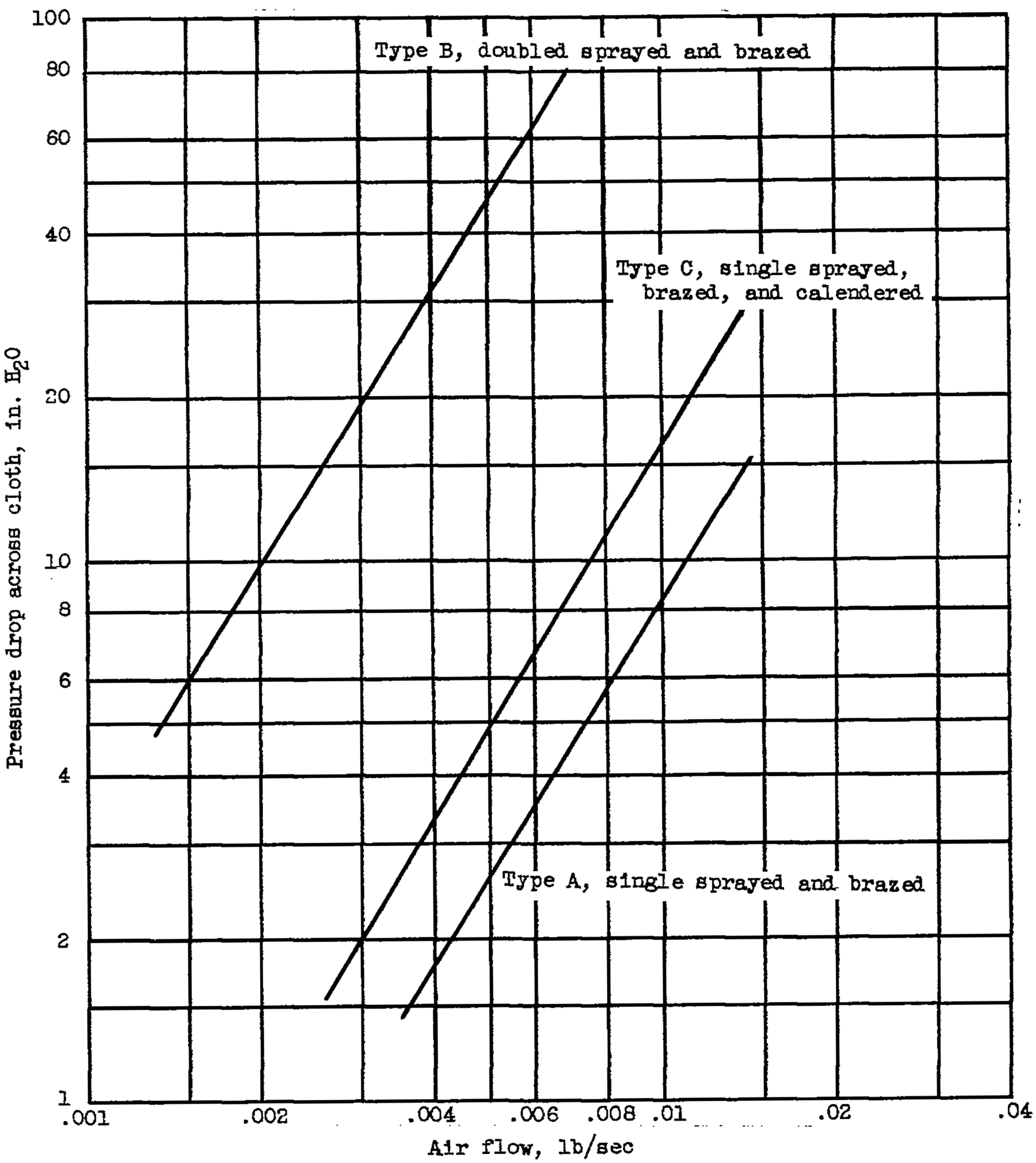


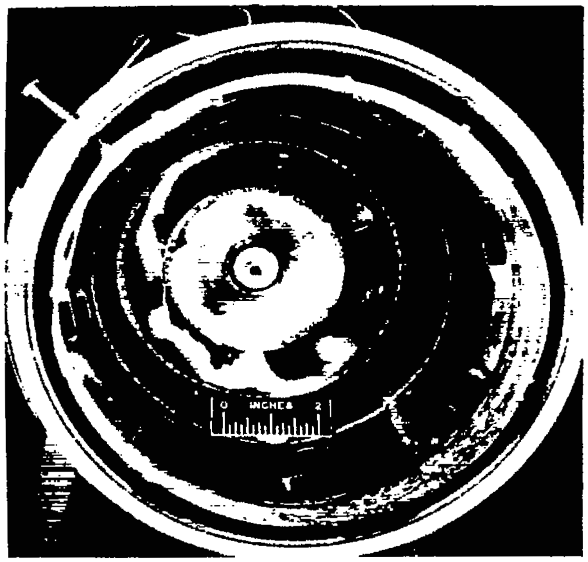
Figure 10. - Porosities of 20×200 mesh wire cloth after processing. Area of test specimen, 1.76 square inches; air pressure downstream of cloth, 29.1 inches of mercury; air temperature, 60° F.

(a) Combustor.

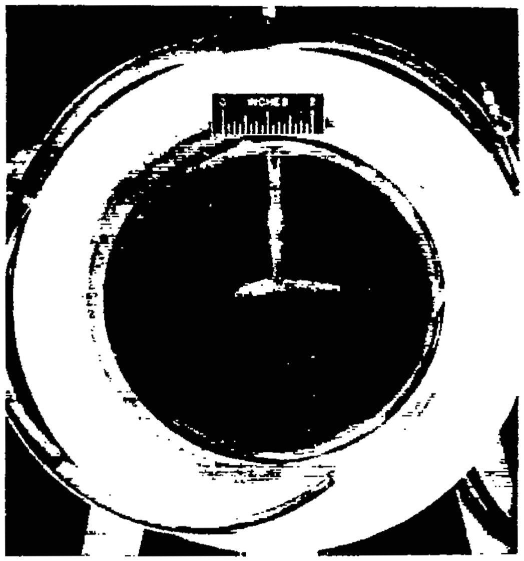
(b) Transition section.

Figure 11. - Deposits from combustion of pentaborane at test condition A. Run 56; test duration, 9.4 minutes.

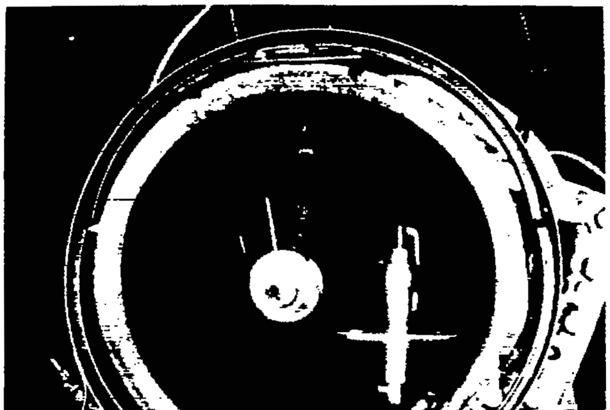
3126



(a) Combustor.



(b) Transition section.



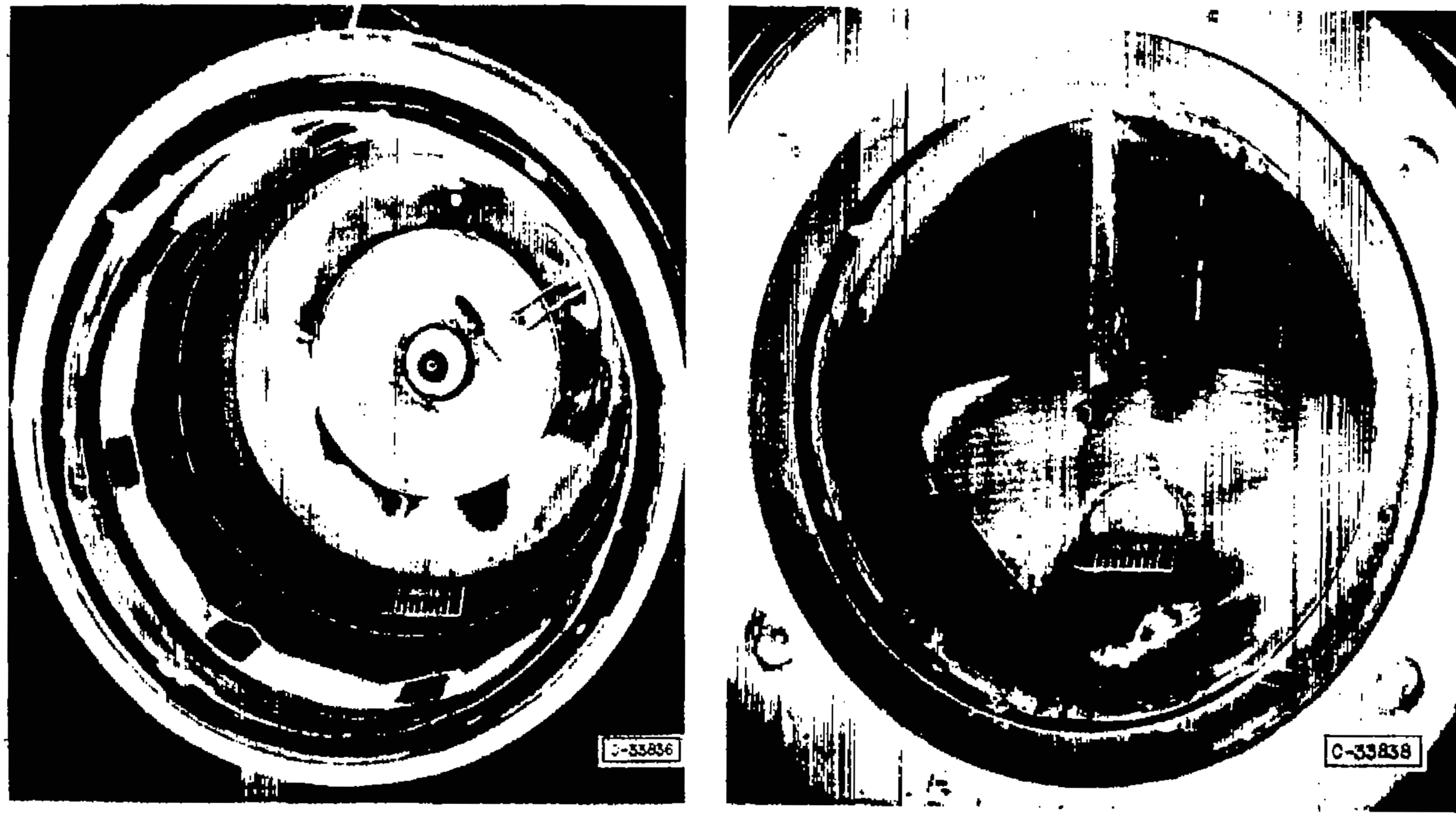
(c) Fuel nozzle and spark plug.

Figure 12. - Deposits from combustion of pentaborane at test condition B. Run 55; test duration, 4.4 minutes.

(a) Combustor.

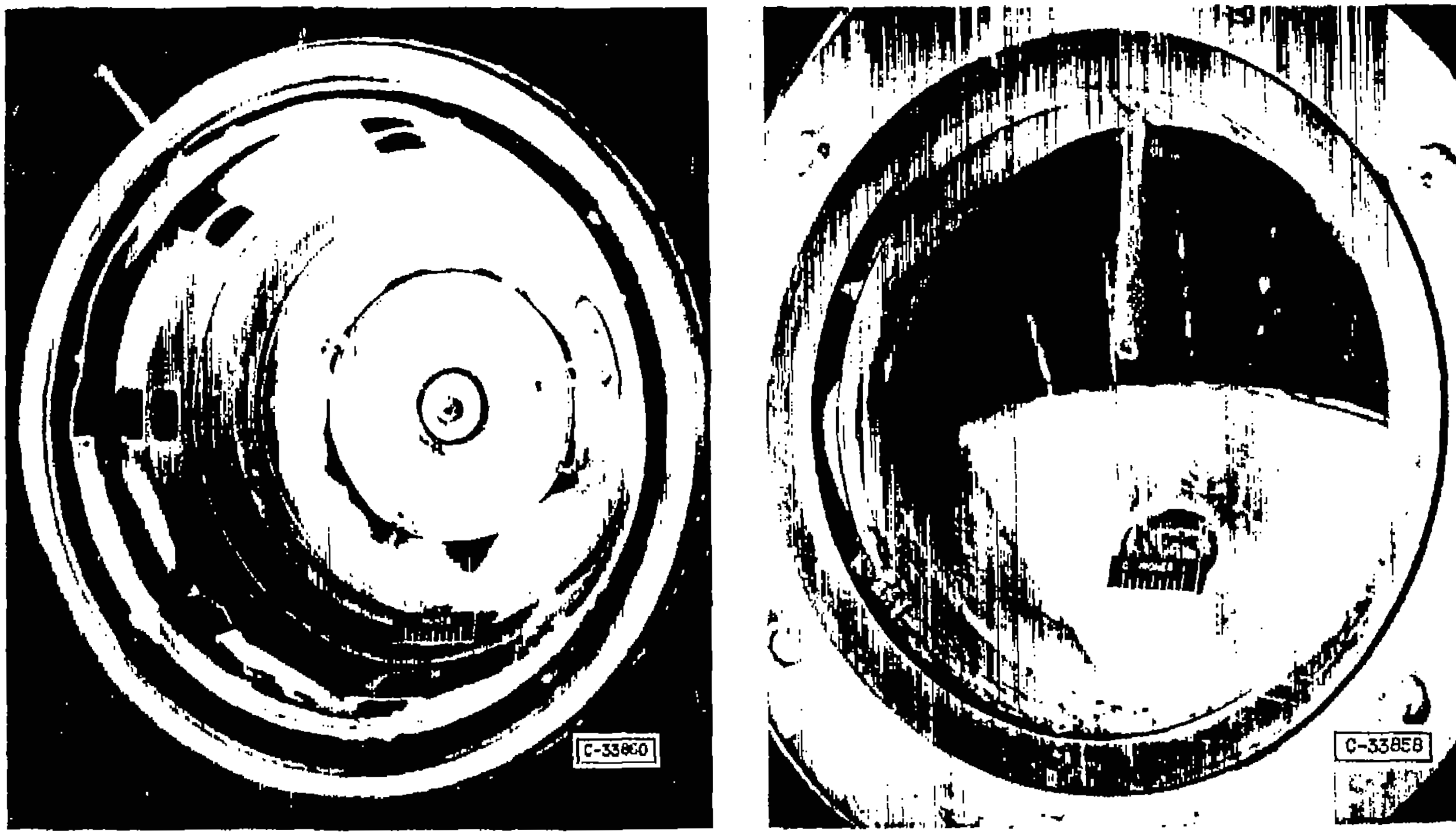
(b) Transition section.

Figure 13. - Deposits from combustion of pentaborane at test condition C. Run 60; test duration, 13.3 minutes.



(a) Combustor. (b) Transition section.

Figure 14. - Deposits obtained from combustion of pentaborane at test condition D. Run 61; test duration, 12.6 minutes.



(a) Combustor.

(b) Transition section.

Figure 15. - Deposits from combustion of pentaborane at test condition E. Run 63; test duration, 6.4 minutes.

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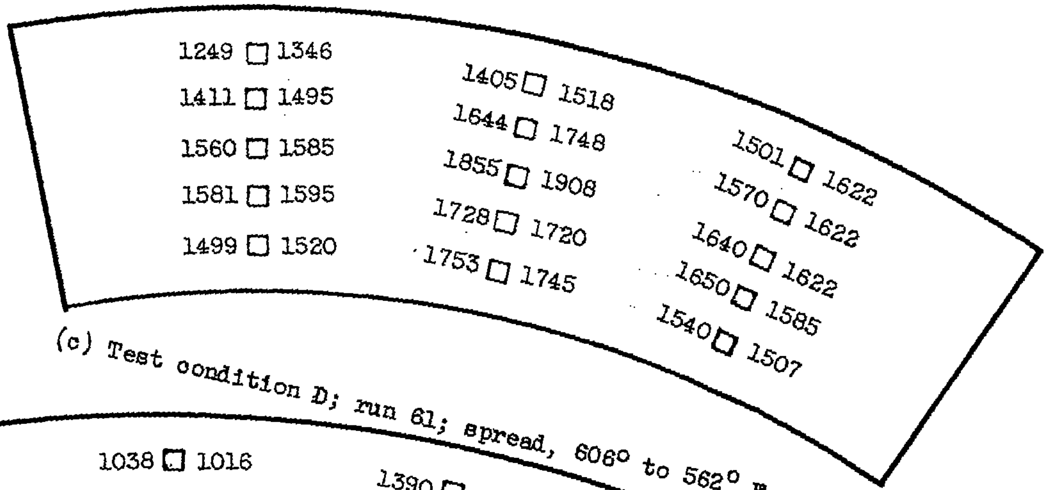
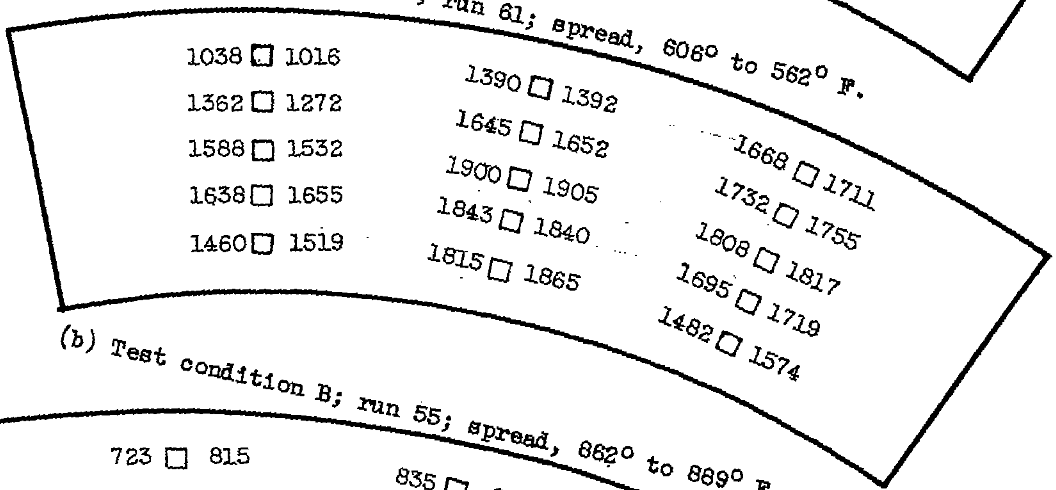
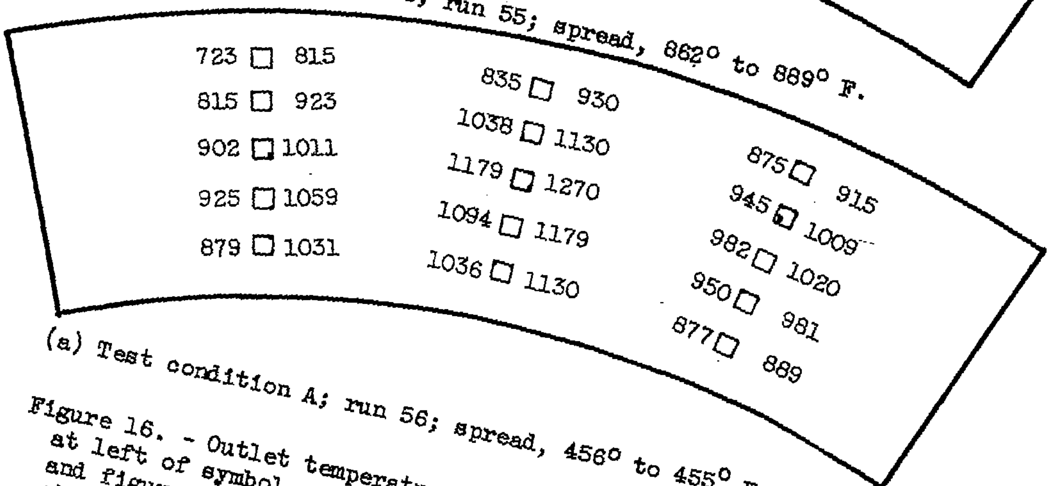
3126



(c) Test condition D; run 61; spread, 606° to 562° F.



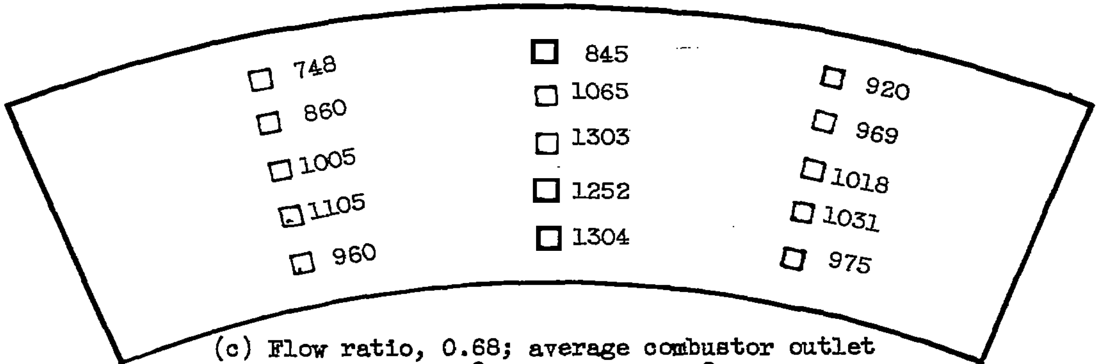
(b) Test condition B; run 55; spread, 862° to 889° F.



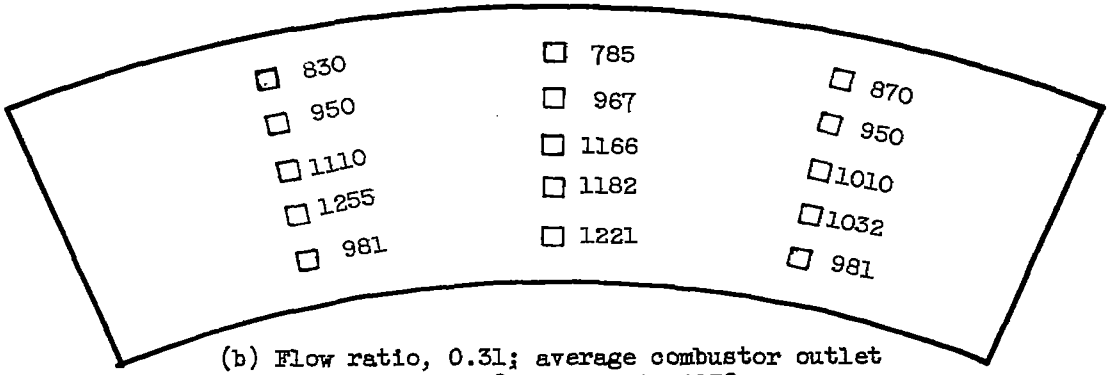
(a) Test condition A; run 56; spread, 456° to 455° F.

Figure 16. - Outlet temperatures for pentaborance fuel. Figures at left of symbol were obtained within 2 minutes after ignition and figures at right of symbol were obtained just prior to shutdown.

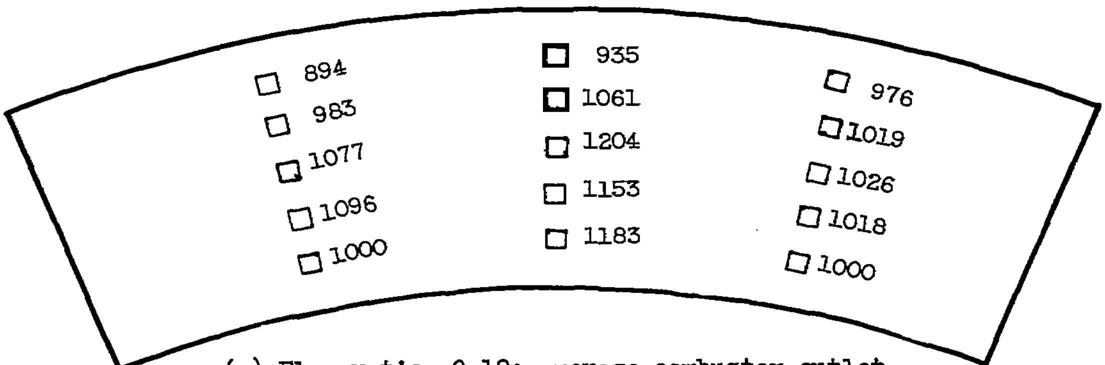
[redacted]



(c) Flow ratio, 0.68; average combustor outlet temperature, 994° F; spread, 556° F.

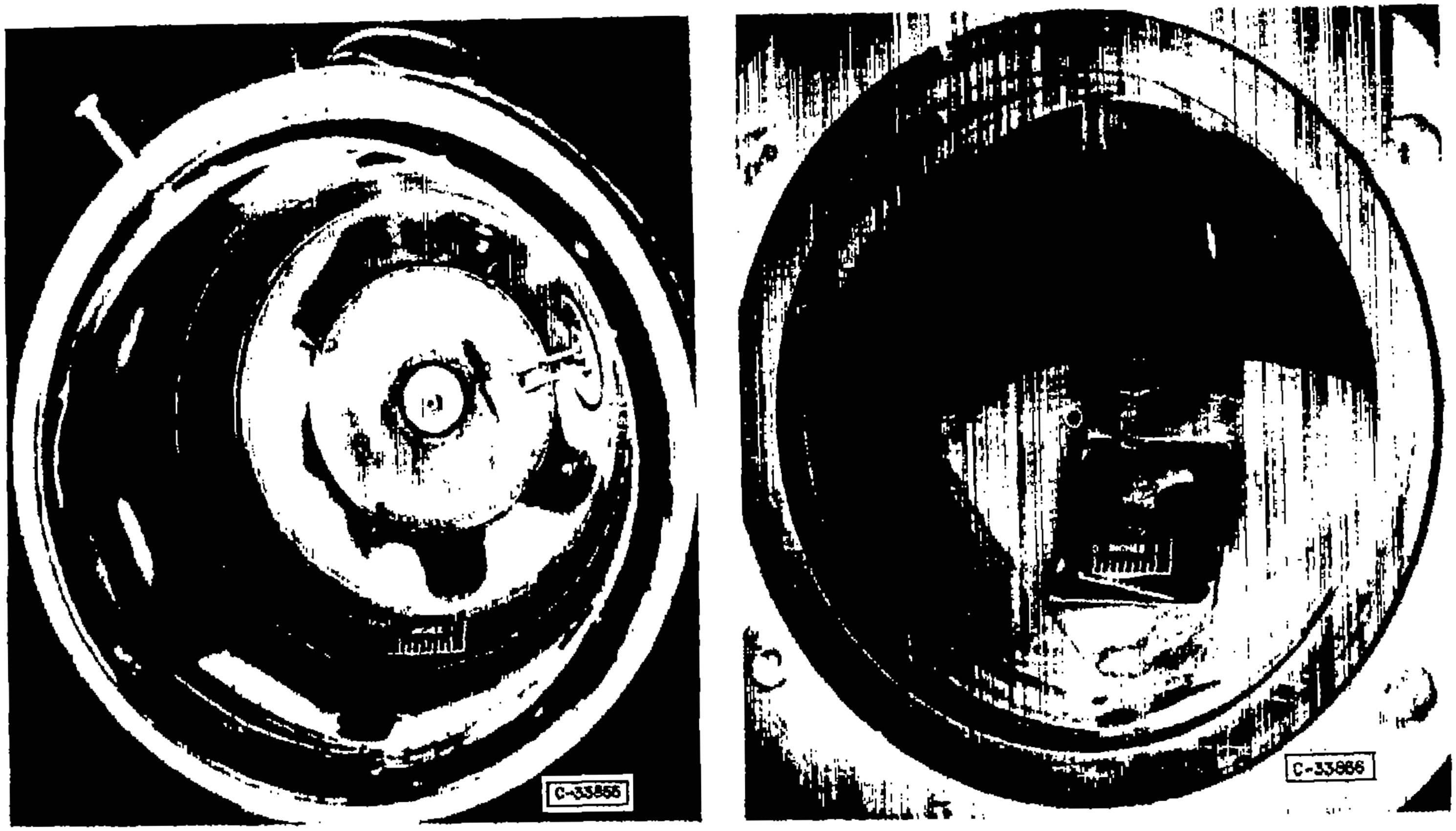


(b) Flow ratio, 0.31; average combustor outlet temperature, 1008° F; spread, 425° F.



(a) Flow ratio, 0.19; average combustor outlet temperature, 1017° F; spread, 310° F.

Figure 17. - Outlet temperature profile for several ratios of atomizing-air flow to pentaborane flow. Test condition C; run 60.



(a) Combustor.

(b) Transition section.

Figure 18. - Deposits from combustion of a blend containing 64.2 percent pentaborane in JP-4 MIL-F-5624A fuel. Condition D; test duration, 8.1 minutes; run 62.

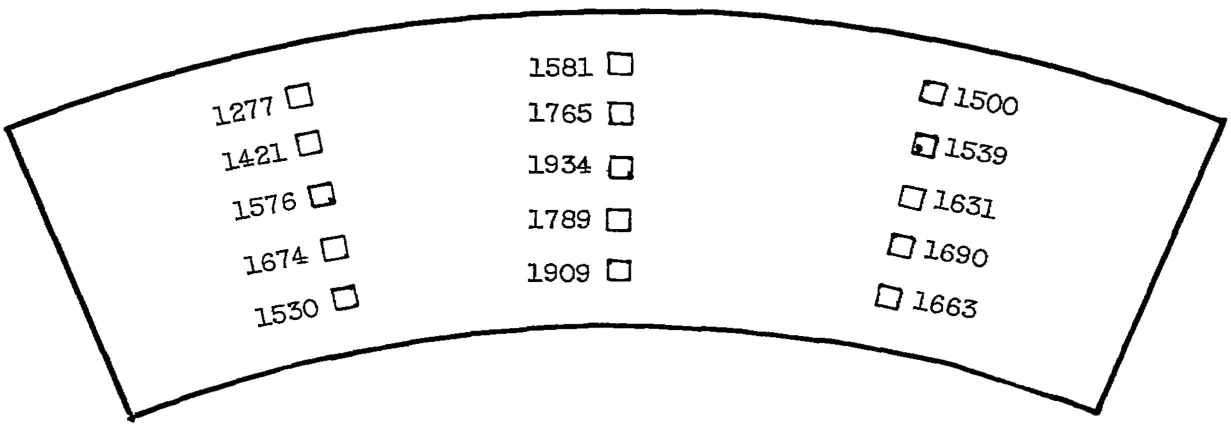
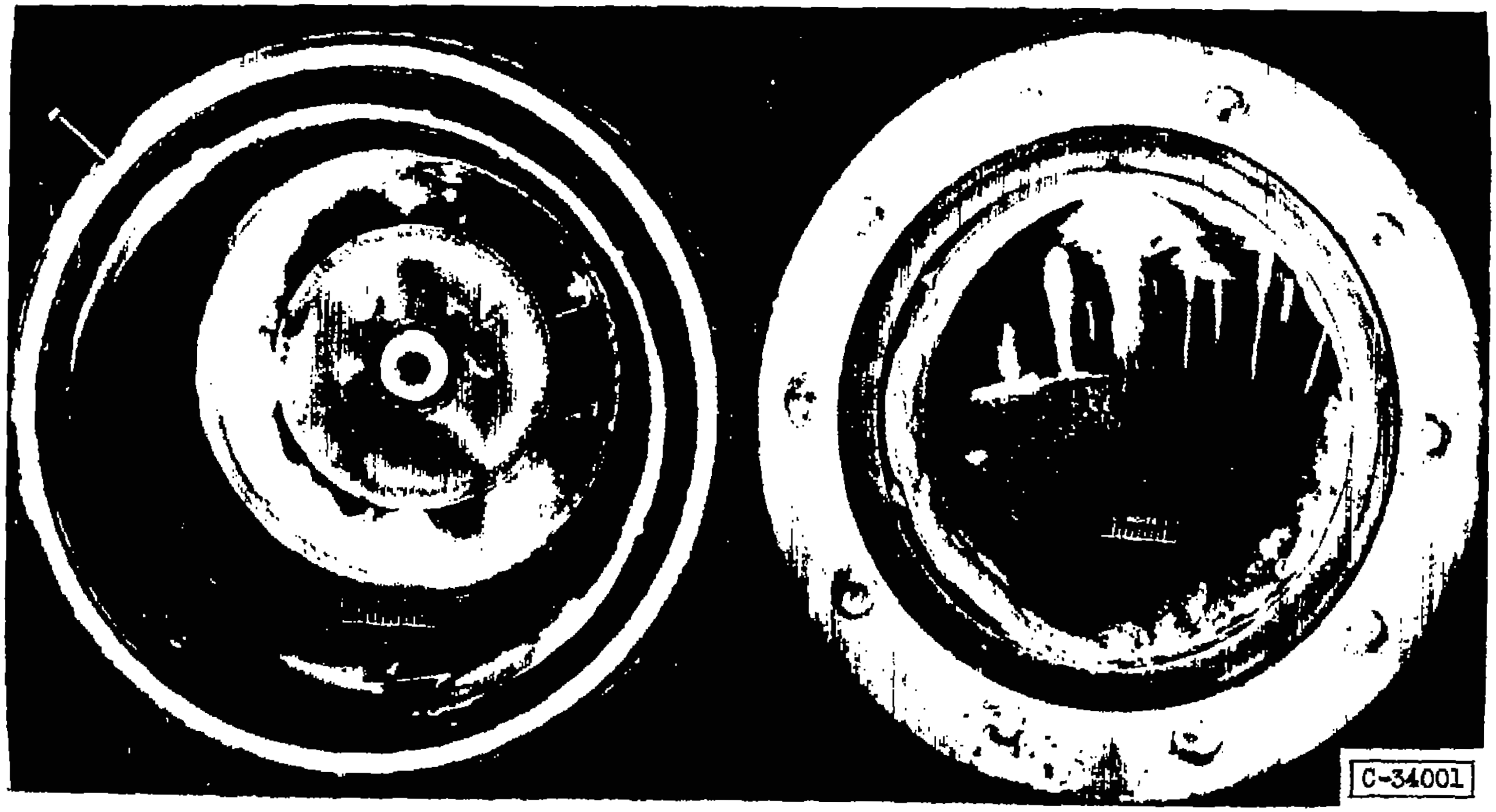


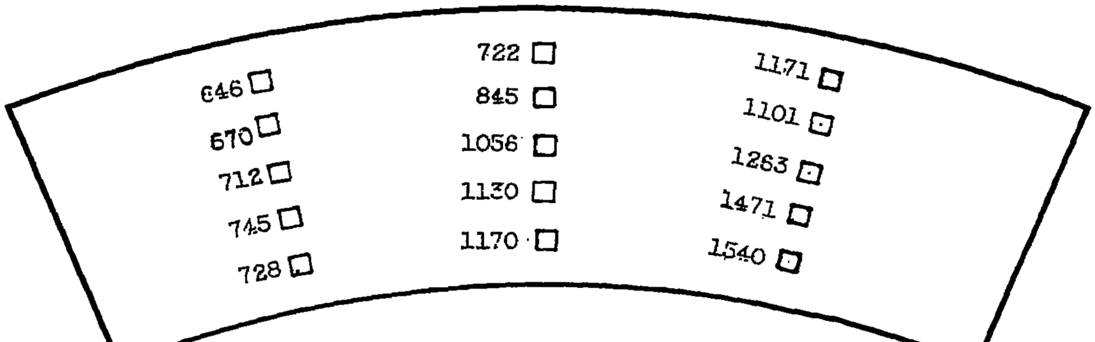
Figure 19. - Outlet temperature for a fuel blend of 64.2 percent pentaborane and 35.8 percent JP-4, MIL-F-5624A fuel; spread, 657° F. Run 62; test condition D. Data obtained 7.2 minutes after ignition.



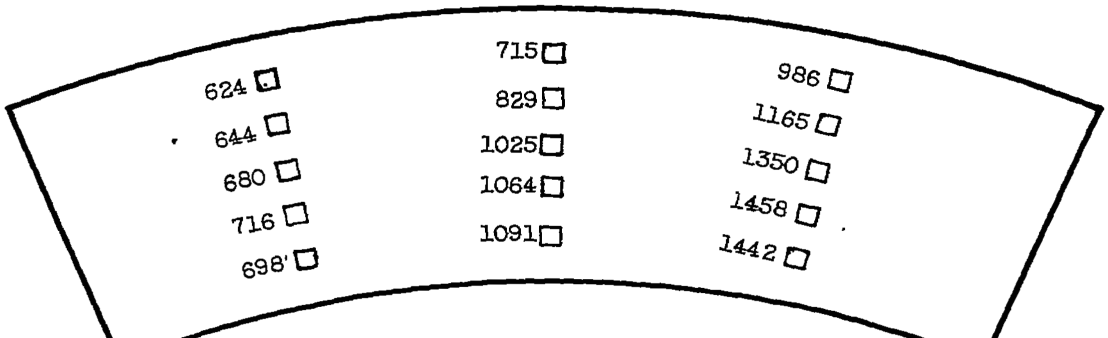
(a) Combustor.

(b) Transition section

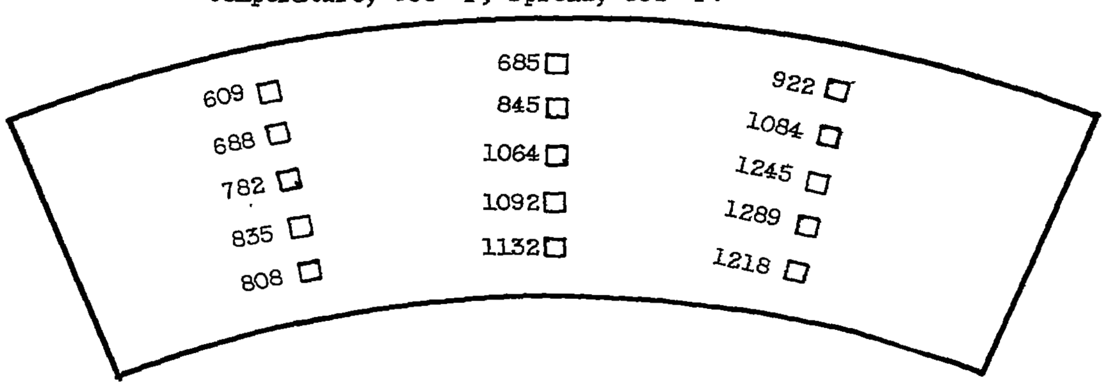
Figure 20. - Deposits obtained during run 57 from combustion of pentaborane at test condition C. Test duration, 21.4 minutes.



(c) Time after ignition, 20 minutes; average outlet temperature, 975° F; spread, 894° F.



(b) Time after ignition, 14.1 minutes; average outlet temperature, 938° F; spread, 834° F.



(a) Time after ignition, 2 minutes; average outlet temperature, 918° F; spread, 680° F.

Figure 21. - Effect of deposits at fuel-injection nozzle tip on outlet temperature profile. Run 57; test condition C.

[redacted]